J. Lindmayer's abstract is presented here. His paper and visual material were not presented for publication.

# HISTORICAL PERSPECTIVE OF BARRIERS TO ACHIEVING HIGH-EFFICIENCY SILICON SOLAR CELLS

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Early silicon solar cells were made of metallurgical-grade silicon with very low efficiency; this was accomplished before the p-n junction theory was understood. The single-crystal silicon introduced in the mid-50's abruptly increased the efficiency to the 5% to 10% region. Throughout the 1960s significant research money was spent to establish the technology of the 2 x 2 cm or 2 x 4 cm space solar cell with 10% efficiency. At this point a certain plateau has developed.

In the early 1970s work related to the violet cell upset the status quo and space solar cells and cells in general became significantly more efficient. The rest of the decade became characterized by establishing a terrestrial photovoltaic technology to support the development of a new industry. Costs per watt became the dominant consideration and frequently the efficiency was compromised. This mentality is present even today as the terrestrial photovoltaic industry continues to develop. Attempts to introduce new materials and other forms of silicon dropped the efficiency and it is now a state of mind that accomplishing 10% efficiency with some alternative combination is regarded as success.

Silicon solar cells are clearly capable of delivering efficiencies much greater than 10%. As the photovoltaic industry will show signs of stabilization, the attention will once again focus on achieving the manufacturable higher efficiency solar cells.

## DISCUSSION

PRINCE: As everyone here knows, you have been very forthright in pursuing semicrystalline silicon, and I am just wondering what your feelings are as to the ultimate potential efficiency that one can obtain from such materials? Have you given much thought to this?

LINDMAYER: I think that very frequently the efficiency is somewhat lower than normal single crystal Czochralski material. In getting into this kind of crystallization, anybody who works with it will know that it creates a whole set of new unanswered questions. But I think the efficiency is just a little bit, maybe just 5% or 10%, lower than normal single crystal at this time.

LESK: Joe, in Kris Koliwad's introductory remarks, he indicated that the objective was 15% efficiency in a module -- it wasn't on the slide -- but then he said the price has got to be a lot lower than it is now. His price projects to $\$90/m^2$ of substrate in the module, if you allow perhaps half of that for the cast polysilicon substrate. Do you feel it will ever get to that price, considering that we still lack 15% efficiency?

LINDMAYER: This is a difficult question. Right now I think we are running a gap to start with. I think if we had much better personnel, or much better-educated people in the production lines and among those running production lines -- there is a gap of maybe 12% to 13% already and that 15% would be possible to achieve. After all, many of us sit down in the lab and generate solar cells that are 15% or better. But somehow the production line never does it. So I think the 15% goal is achievable, definitely in the lab, anyway. But production is something else.

PRINCE: I think we should bring up one other point before we go on. In order to get this 15% module that Kris mentioned, we need to have cells that are about 18% efficient because you have losses in assembling these cells into the module, and covering the module with some protection, and lost area, and so forth. So when we talk about 15% modules, it means about an 18% cell in production, which may mean a 20% cell or a 21% cell in the laboratory. I do remember from an early experience that if you can do it in a laboratory, you can transfer to very good production people, then you can then produce exactly the same quality in the production line.

LINDMAYER: Yes. This is an important point. A 15% panel efficiency requires very much higher-efficiency cells.

LOFERSKI: I am surprised that you are saying that the problem is with the education level of people on the production line. It seems to me that if you have a good production line going, it has to be do-able with all the kinds of people that you have presently on production lines, basically. If you want to hold the price down, you can't have Ph.D.'s making solar cells, so I think it is not in the education of the people but rather in the industrial engineering that is involved or in manufacturing engineering, carrying things from the laboratory into production. We have to be

able to make that transition. After all, when Arnie asked you about the price at that 15% module efficiency, $90/m$^2$, it means $0.60 per peak watt and we can't even make the current 10% efficient cells at $0.60 per peak watt, so there is a lot to be done; there is a big gap between where we are now and what is required by 1988. But anyway, I would like your comment on this business of who is on the production line now. I am surprised at that comment that you need better people.

LINDMAYER: Well, I was merely referring to middle management. True Ph.D.'s cannot run a production line. They have never succeeded. I am not advocating that there should be more Ph.D.s on the production line. The workers themselves do routine work, so it is the middle management in technical capacities that is really missing. But with respect to the other goal, getting down to $90/m$^2$, I think it is going to be hard.

DYER: It is interesting that in the early 1950s, when Mark Shepard was head of Texas Instruments' production of semiconductor devices, he wrote an article, "Ph.D.'s on the Production Line," and the results are evident. I think what you are saying, Joe, is that in the early stages, that is what you need. Once it becomes a mature product, you can't afford it. But to get it going right, there is nothing wrong with it.

PRINCE: Are there any other questions? Yes, Gene.

RALPH: Joe, I think I see a conflict between what you practice and what you preach. Not just you but other companies as well. I think there is a definite feeling that making something cheaper means going to simpler and less sophisticated approaches, and I put the contacting systems, the use of the Semix type of materials, in that category. You give away efficiency in the hope of getting lower-cost processing, and of getting immediate gains that way. But you say now that you agree that the 15% module goal is really the right thing to go to. Now, it sounds to me as though your middle management or even your top management has to be educated then in the difference -- getting immediate cost gains by going to simple, cheap processing that gives you lower efficiency, versus very sophisticated processing that has to be automated or robotized or whatever it is to get the cost down. Are you saying that you are ready, or you would see management -- see that new approach to 15% being the right way, or are we going to go back to the old way?

LINDMAYER: Any technology change results in some efficiency drop but can be mmediately observed as climbing up again in time as people begin to master that technology and understand its details. So sometimes it is very difficult to tell in advance that a technology change is automatically compromising efficiency. I think it is just a philosophical point.

MILSTEIN: I would like to comment that in the way our high-efficiency program has been conducted over the past year or two we have not, as we stated in the RFP that we issued in 1982, considered the matter of cost reduction. That is something that we feel is best left to industry. The point of doing that, though, is that it allows a researcher to investigate techniques that at the present time may be extremely expensive, but that

may lead to understanding or additional capability. They then may be re-engineered or reconfigured in some way to be done for less expense at the time you want to put them into production. In that sense, the conception of artificially holding down the cost, if you apply it to research, may simply prevent you from looking at techniques that you would otherwise be able to examine. You may miss something.

LINDMAYER: I don't think we have any real conflict here. Dr. Koliwad carefully put the emphasis on the cost because, as the industry is now, industry has put in more private money than the government has put into this program. And it is going to be doing more of this.

LANDSBERG: The discussion has prompted me to ask you a question, Mort, about the DOE program. You mentioned two figures, the $90/m^2$ and the 15% efficiency. Why not just give the $90/m^2$? Why is the efficiency constraint given as well? I mean, you have a very cheap amorphous cell that does better than $90/m^2$ but is less than 10% efficient. What do you say about that?

PRINCE: It is very straightforward, Peter. If you have a 5% cell versus a 15% cell or module, you need three times the area; the land cost, the wiring cost, and so forth. There are many other costs that go up, and that is why you need the combination of both parameters.

LINDMAYER: I also believe, if I could add to this, that maybe it is more appropriate for DOE to set up technology and scientific goals than R&D goals and economic goals at this point in time.

WOLF: Joe, you mentioned that it is often advantageous to introduce a somewhat cheaper process and take a loss in efficiency, and the efficiency may come back as we gain experience. This in some cases may happen. On the other hand, the opposite can also easily be the case: you move a step to higher efficiency, but at a higher cost, and then you are learning as your production teaches you how to do this more and more cheaply. In fact, it seems to me if you go the other way, you also have to be very careful in evaluating whether the cheaper process does not have a limit that doesn't permit you to get back more efficiency. You mentioned metallization screen printing. You use relatively expensive metals, but you never get low resistivity, you always end up with a higher resistivity in the center of materials, it seems. So you have a penalty. It seems you cannot get through narrower lines with the screen printing process than you can with some other processes. You may have to -- toward the beginning -- say yes, it would give me a cheaper process, but I don't see where it can get me back to the higher efficiencies. I think you have to evaluate it carefully before you make a decision of this sort.

LINDMAYER: I agree with you that there are two sides of this equation.

PRINCE: I think we have to be careful that we don't get off into the cost aspects of silicon cells and modules. This meeting is about efficiency, so unless you have a specific question relating to efficiency and not cost, please hold them for a discussion during the coffee break.

SCHWUTTKE: Joe, I would like to pick up on that comment you made, that we need better education in manufacturing. I look at it in a different way. I don't think we really need better education in manufacturing. We are confronted by a situation where you have relatively, and I say relatively, little or indifferent education on one side, and on the other side, the Ph.D. side, we have relatively too much education. You really are confronted with a problem; you are dealing with two different types of people, and this is the problem you have. It is a communication problem; the manufacturing guy does not respect the Ph.D. guy, the Ph.D. guy does not respect the manufacturing guy, so what you end up with is the following situation (I have seen this over the years over and over and over again): you have two efforts running parallel and these two characters never talk to each other, the manufacturing guys want to outdo the Ph.D.'s, and the Ph.D.'s want to outdo the manufacturing people. I think what we need is not better education; we need better communication, and that could save us an awful lot of money.

LINDMAYER: Very good point.

SIRTL: Mort, I come back to your comment about "let's not talk about economy, let's talk about high efficiency." I think it can be a dangerous attitude, at least in part, because an 18% solar cell, even in space technology, is not reality today on a 10 x 10 $cm^2$ substrate, and if we talk about the best we could do about making high-efficiency cells at present, we have to talk about float-zone material. It may be very nice to explore the best material available -- some mechanisms we don't understand -- but I think we should be careful not to emphasize too much that kind of investigation alone. After all we have learned to date, float-zone material would not be a good material as a basis for economical production, so we may be forced to switch too late to other systems that offer a much more economical background for making the solar cells. I just wanted to bring up that point because the float-zone defect situation, for instance, is much different from any kind of polycrystalline material or whatever else you may choose.

PRINCE: You have a very good point there. In fact, I talked with Ted Ciszek specifically about this problem: can we produce float-zone material at a similar cost to Czochralski material; he has given me some positive indication that it is possible. I don't know whether we should make comments about this at this time, or later.

SCHUMACHER: I would like to know if anyone has ever built a module that would give you 15% efficiency regardless of whether it was done by Ph.D.'s or who have you, and if not, why wouldn't that be a good objective -- just to assemble the best team you could and build the very best module you ever could -- and then you can begin as a second priority to go after reaching this cost objective. I happen to think that single-crystalline silicon would be a very nice thing to use in these solar cells. I would think you would try to get the very most out of it that you could, and I think that would be the ideal approach.

LINDMAYER: I think that at least small panels have been made that are good, but not 1 $m^2$. This was really just done in the lab.